E UNIVERSITY OF CHICAGO

Round Table

New Research in High-Energy Physics

An NBC Radio Discussion by SAMUEL K. ALLISON
MARCEL SCHEIN *and* MALCOLM P. SHARP

Including

ATOM AND VOID IN THE THIRD MILLENNIUM

By J. ROBERT OPPENHEIMER

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ATOM AND VOID IN THE THIRD MILLENNIUM

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THE UNIVERSITY OF CHICAGO ROUND TABLE

CATHERINE D. JOHNSON, *Acting Director and Editor*

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New Research in High-Energy Physics

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Recently, at the meetings of the American Physical Society, Professor Marcel Schein of the University of Chicago presented evidence of an atomic particle collision which created a greater burst of energy than any ever observed before in single particles—even in the biggest atom-smashers. He reported that about ten million billion electron volts were released when an invisible particle from outer space smashed into a small aluminum-wrapped package which hung from a balloon which was one hundred thousand feet above the ground, flying over Texas last winter. This ROUND TABLE *tells you about this event and its importance to basic science.*

MR. SHARP: This is a program by two physicists dealing with the discovery recently made by one of them. I am here as a layman to ask questions designed to keep the discussion within the range of ordinary people's understanding, or somewhere near it. First is Professor Allison, professor of physics at the University of Chicago since 1930. He is the director of the Institute for Nuclear Studies—a branch of the University devoted to basic research in physics and chemistry.

Professor Allison, I used to see balloons going up from Stagg Field in the old days when I passed it, and I assume that those balloons had something to do with your work.

MR. ALLISON: That is not quite true. The balloons were part of research in physics, and we are very fortunate to have this afternoon the balloon expert around here, Professor Marcel Schein, who is professor of physics and also a member of the Institute for Nuclear Studies. Mr. Schein has been sending up balloons for a long time, even before the Institute was founded; and during the period he has been sending up balloons the techniques have improved and changed in finding things with them. I hope that we will be able to find out from him some of the things which are going on nowadays in this type of research.

MR. SCHEIN: We are trying to explore the field of high-energy physics by sending up balloons to the stratosphere, in altitudes corresponding to about eighty to a hundred thousand feet. The reason why we are doing this is to find out whether the cosmic radiation, which is present at these high altitudes, interacts with nuclei and produces some new kind of spectacular events or new particles in physics. This is of the greatest interest for finding out what are the fundamental laws of nuclear physics and high-energy physics.

MR. SHARP: The newspapers, a week or two ago, carried news which indicated that in this prospecting you had struck very remarkable "pay dirt" recently. Is that so?

MR. SCHEIN: Yes. I have here to be very conservative and very cautious, because scientific discoveries usually do not happen overnight, and it takes very careful exploration until we really can draw conclusions which are absolutely definite.

However, the event which we have found recently in a balloon flight which was launched, through the courtesy of the Office of Naval Research, from Texas revealed an entirely new type of event which we have never seen before. Therefore, we got excited about the nature of these events.

MR. SHARP: How long have you been sending up balloons?

MR. SCHEIN: We have been sending up balloons since 1938, and from Chicago we have had approximately eighty-nine balloon flights. However, we are using the facilities of the Navy too, and they cooperate by sending up balloons from all parts of the world. We have had expeditions to Cuba. We have had also expeditions to the North Pole. We are also sending up balloons from Texas and from Minneapolis, where a lot of new results can be obtained on these new questions of high-energy physics.

MR. SHARP: The balloons I used to see were little ones. You use others, too?

MR. SCHEIN: Yes, the balloons used in Chicago have been mostly little ones. But on certain occasions we use large ones, which have been supplied by the Office of Naval Research. The balloons used in Texas, Minneapolis, and other places were large plastic balloons which have a diameter of over a hundred feet and look very spectacular when we watch them, even in the stratosphere.

MR. ALLISON: Maybe some of the people might be interested in what goes up in these balloons to make observations at these very high altitudes. In the old days, I believe, Mr. Schein used to send up Geiger counters, which we all know about in prospecting for uranium nowadays, but more recently much of the work has been done with photographic plates. It has been found possible to make especially sensitive emulsions on these plates, so that if a high-energy particle produced in the upper atmosphere or actually flying into it from outside space passes through this emulsion on the photographic plate, a string of dots develops when the plate is developed; and we see the trace of the particle having passed through. These plates are actually sent up there; and then they are brought down and developed and scanned or looked at carefully through microscopes, shifting the plate along, little by little, and looking for traces of unusual events.

One of the events which Marcel Schein and his group have just seen is a very unusual one, and I hope that he will tell you a little more about it.

MR. SHARP: How about handling the balloons when they come down? Do you have any problems there?

MR. SCHEIN: We are very fortunate to be in the Middle West here, because of the fact that, if we have the correct weather predictions regarding the wind direction in the stratosphere, then our balloons usually land in an area which is well populated, and the farmers are extremely cooperative in recovering the balloons. However, if winds are very strong, the balloons can drift and in a few hours they can drift as far as the Adirondack Mountains, West Virginia. We even have found them in Canada in distances over five hundred miles. Occasionally we have very peculiar occurrences in connection with the recovery. People sometimes are afraid that they might be atomic bombs or that they are carrying atomic bombs or some very peculiar instruments. However, these occurrences are very rare, and the farmers in the Middle West are well accustomed now to the problem of recovering balloons.

MR. SHARP: Do the balloons ever come down in unexpected places and cause trouble?

MR. SCHEIN: Not particularly. We are usually notified. Most of the authorities in the area where they are expected to land have been told, and we have really no great problem of recovering them.

MR. SHARP: You told a group once about some of them coming down in fishnets?

MR. SCHEIN: Yes, that is true. We had a very unusual occurrence on Lake Erie once, where fishermen were looking for some fish; and one day they found that something heavy had landed in their net. When they tried to pull the net up, they found that it was a balloon apparatus. They notified us, and it was a rather strange occurrence that from Chicago we actually hit a fisher net in Lake Erie with our instruments.

MR. SHARP: Why do you do this, Mr. Schein? Is this for fun? Do you get some information up there? What does it lead to?

MR. SCHEIN: It is true that it is great fun to do science and to use balloons in this connection; but we think that recent developments show that there is more to it than fun—that actually a large number of new things have been found in balloon experiments.

MR. SHARP: There is nothing against fun. It is probably a good reason for doing a lot of scientific work, is it not, Allison?

MR. ALLISON: I think basically most physicists would admit or state that they do physics, at least research in physics, because it is fun. I mean, we like to work in the laboratory; and it is most exciting and pleasing if it happens once in a lifetime, perhaps, that we make an important discovery.

MR. SHARP: You speak about the laboratory. But why balloons?

MR. ALLISON: The point seems to be this: That raining in on the earth from outside space are particles traveling with extremely high energies, much higher than we can produce in our cyclotrons and in our artificial equipment. When these particles strike the air of the earth, the upper limits of the atmosphere, very strange things happen due to their extremely high energy. They create a host of new particles which may live only a short time; they are very short-lived things but of great interest. They live long enough to go through these photographic plates about which I spoke and to be detected. In that way, by getting up to the upper limits of the atmosphere where these particles are still fresh, let us say, just recently created, we can trap some of them and study them. Now we have a whole host of new particles which make the picture much more complicated than it used

to be thirty years ago when we thought the universe was made of protons and electrons.

MR. SHARP: Years ago, when I used to try to understand these matters, there was a kind of working diagram with a proton in the middle and electrons revolving on the outside; but I developed, from talking with physicist friends, a little doubt about that working model. They seemed to be talking about electrical discharges and mathematical formulae and things of that sort. I never quite got over that doubt. But I understand that this is the world in which the physicist lives, only now very much complicated. Is that right, Schein?

MR. SCHEIN: That is correct to some extent. It is true that the outside of an atom can still be described correctly by applying electromagnetic theory to protons and electrons; but, as we are moving deeper into the inside of the atom, we find ourselves in a position that we have protons and neutrons and also these many other particles which Mr. Allison mentioned. This is a thrilling new experience; and we feel that it is one of the most interesting things which has been revealed in physics. Now we have to integrate this knowledge of new particles into our whole picture of physics; otherwise, it seems impossible to understand the basic laws in which the nucleus and the universe both are involved.

MR. SHARP: How many kinds of particles have you now?

MR. ALLISON: That is sort of an embarrassing question to ask a physicist, because the number more or less keeps changing. I do not want to commit myself further than to say that there are about twenty new particles which have been discovered. The situation is something like this: Isolated observers all over the world record new events; and, once a year or so, there is a big conference somewhere. They all get together, and often it turns out that two particles described by different observers—and each one thought that they were different—turn out to be the same; or they find out that one of them really is different. Thus the number which is universally recognized as fundamental and new keeps varying. But I would say that there are about twenty particles nowadays that we just do not know how to fit into our scheme of the universe.

MR. SHARP: How are they classified?

MR. SCHEIN: It is really a very difficult question to classify them,

since we have so little knowledge about many of them. However, we know certain basic facts about them. One is that we can classify them by their mass and by their electric charge. That classification would lead to the following picture: We have a particle which we call the photon, which has at rest exactly a mass which is equal to zero; and we have a neutrino which also is uncharged and which has a mass which is unknown to us. It might be close to zero. Then, we have positive and negative electrons, which have a very definite mass and which have been measured up to four decimal places with high precision. Then we have particles which we call mesons which have masses intermediate between the electron and the proton, which is our important particle and which is stable. All the mesons are unstable and disintegrate in a very short time. Some of them live for only as short as ten-billionths of a second, but we still can detect them with high precision. Then we have particles which are unstable and heavier than the proton. The neutron is unstable and lives for about thirteen minutes. Then we have the so-called hyperons, which have masses considerably heavier than the proton, which run up to about four thousand times the electron mass, whereas the proton has a mass of only around eighteen hundred and thirty-six times the electron mass. That is, the hyperon is more than twice as heavy as a proton.

MR. SHARP: What the physicist calls "mass" has some approximate similarity to what we call "weight." It could be expressed in grams and ounces. Is that right?

MR. SCHEIN: Yes, that is correct. We can express masses in grams. However, these so-called fundamental particles have such small masses that they would be very difficult to express unless we want to go to very minute quantities. It would be impossible to put them on a balance and actually weigh them. This is a task which we cannot perform if they are at rest.

MR. SHARP: The photon at the bottom of the scale has no mass but has energy—or is energy?

MR. ALLISON: Yes.

MR. SHARP: That is a mystery.

MR. ALLISON: This business of the rest mass of a photon being zero is a difficult concept, I guess, to acquire; but to a physicist it relates to the amount of disturbance, let us say, or work we have to do to create one.

This radio broadcast is radiating photons to you through the air. If you turn down the power on this station, pretty soon you would not be able to hear me any more; but a delicate instrument could pick it up. If you turn it down still farther and take a more delicate instrument, you could also pick it up; and so on. There is really no threshold, no beginning of power at which the photons begin to come to you from this radio station; and that is what we mean by the rest mass being zero. If this station were communicating to you by means of mesons, for instance, there would have to be an enormous initial power put in to create them, so that they could fly to you with the words which we are saying.

MR. SHARP: Mr. Schein, as I understand it, your new discovery was a particle of relatively high mass, a proton?

MR. SCHEIN: The possibility certainly is not excluded that the new particle which is involved has high mass and that the event which we observed is actually due to a process in which a proton and the so-called anti-proton annihilate each other. An anti-proton would be the exact image of a proton except that it would carry a negative charge. If we brought the two together in a very small distance and in distances comparable to dimensions of atomic nuclei, then such an annihilation would take place. As a result of this annihilation, a large amount of energy is liberated in the form of photons—photons as described to you by Mr. Allison, except that each of them would carry very high energies and would reveal itself as a gamma ray, radioactive elements, and even of much higher energy than that.

MR. ALLISON: Perhaps we should point out that a similar phenomenon to the annihilation of a negative proton with a positive proton has been known to physicists for quite a while. You see, the positive electron has been discovered now for many years. Originally we just knew negative electrons. They are the common kind which we can get in our X-ray tubes and with which we are familiar. Then we found positive electrons, but they do not live very long, because sooner or later they come in contact with a negative electron, and the mass of both of them disappears in a flash of high-energy radiation.

This is now familiar stuff to us physicists about electrons, and we have been speculating that a similar thing might occur between a positive proton and its mirror image, or anti-proton, which would be negative. And it is possible that the curious event which Mr. Schein

has observed in his photographic plates might be a trace of such a thing's having happened.

MR. SHARP: Mr. Schein, you are being very conservative in refusing to speculate now. How about telling us what you really think about the phenomenon which you have observed.

MR. SCHEIN: We have tried our best to fit together all kinds of other events which would explain the fact that we are observing here a burst of photons of very high energy on the photographic plate which materialize into positive and negative electrons; and, in that way, we can see their path through the plate.

Now, these high-energy photons are usually accompanied by other charged particles; and we always see other particles like protons or mesons or any other kind of charged objects which are knocked out from a high-energy collision. But in this particular event we could not find any trace of a charged particle at all; and therefore it is completely new to us what could have happened.

However, the energy is so enormously high in the event—we estimate that it is more than a million times a billion electron volts—that this makes us feel that we have involved here the annihilation of a cosmic-ray particle. Since we have in the cosmic radiation only protons and heavier nuclei as primaries coming in and since the event has been observed at an altitude of a hundred thousand feet, we think that this is a possible explanation for the event: That the most probable particle in the cosmic radiation, namely, the proton, has a mirror image, the anti-proton, and it is annihilated when it meets an ordinary proton in the aluminum which covers the plates.

MR. SHARP: You spoke of an astronomical number of volts a minute ago. What does that mean?

MR. ALLISON: You see, in any branch of human activity we have to have units with which to measure things; and we usually use units which are comparable in size to the things which we are measuring. That is, nobody uses tons as a unit for weighing out diamonds. Diamonds are too small to be weighed by the ton. And the amount of energy which an electron can have is too small to be measured by the ordinary large-scale units of energy. So we have invented one which we call the electron volt. The amount of energy in one electron volt, as someone pointed out, is not sufficient to knock a mosquito off the

wall, but for that much energy to be possessed by one single electron means a lot of energy for that little particle.

I might say that the electrons in atoms, the external electrons, have energies of a few tens of electron volts. In an X-ray tube, where the X-rays are generated to take pictures of your teeth, the energies of the individual electrons may be ten thousand to fifty thousand electron volts and so on up.

MR. SHARP: On the other hand, the newspaper stories of Mr. Schein's event, as I read them, indicated that there was even by ordinary, everyday standards a tremendous amount of energy produced—outside the range of that produced by cyclotrons, for example.

MR. SCHEIN: It is true that the total energy involved in the event is way outside the limit which can be reached by any accelerator which exists at the present time. However, since the particle came in with a tremendous speed from outer space—and we are sure of that—a part of the burst of energy which we observed was from this speed. Thus, when this amount of energy is taken out of the situation, it is very well possible that machines will be able to create actually anti-protons, and to produce the annihilation of a proton and an anti-proton because of the fact that some of the machines release enough energy to accomplish this in one single act, if it needs more than two billion electron volts.

MR. SHARP: How would that compare with the energy used in existing cyclotron operations?

MR. SCHEIN: There is a machine at the present time at the University of California which goes up to about six billion volts; and this machine is certainly within the range.

MR. SHARP: So it is conceivable that the kind of reaction which you discovered in outer space could be produced by that machine?

MR. SCHEIN: Yes.

MR. SHARP: Then it is possible that your discoveries have some technological value?

MR. SCHEIN: As a scientist I am no judge of this possibility.

MR. SHARP: Mr. Allison, is this going to increase our supplies of atomic energy for fuel, for bombs, or for medical purposes?

MR. ALLISON: I think that that is way too far in the future to predict.

I would like to point out to people, however, that the type of research about which Mr. Schein has been talking is very complicated and involved to carry out; and without help from government agencies we would really be unable to do this.

The type of research which is being talked about here is sponsored by the Office of Naval Research, a branch of the Navy, working together with the Atomic Energy Commission.

The people who govern this country have come to the conclusion that in these perilous times it is very important for us as a nation to keep abreast of all new developments; in fact, to lead, if possible, in the basic researches which reveal new things about the universe.

ATOM AND VOID IN THE THIRD MILLENNIUM*

By J. ROBERT OPPENHEIMER

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In exploring the atomic world, we have travelled to a new country, strange for those who have lived in the familiar world of Newtonian physics, strange even to Newton's own view of wonder and pre-vision. "God, in the beginning," he wrote, "created such a certain number of Atoms. . . ."

We have our atoms; we are trying to understand them. We have the simplest of the atoms, hydrogen, with a single proton for its nucleus and a single electron to make it up. But the ingredients do not follow Newton's laws of motion. Atoms of hydrogen appear to be all alike; they have a fixed size; they are stable and not transitory; the light that they emit is not what an electron circling in ever smaller ellipses would radiate. They have a stability that does not derive from Newtonian mechanics. When they are disturbed by light or electrons or other matter, they take up energy in definite quanta characteristics for the atom. They are described in terms of states, states that are not orbits, though they have some of the properties of some special orbits. The states are stable, or almost stable. Transition between them, occasioned by disturbance, or occurring spontaneously with the emission of light, occurs by chance. We do not know the cause of the individual transitions but only, at best, their probable distribution in time; nor do we have, in terms of space and time and trajectory, any picture whatever of what these transitions may be. These acausal atoms compose the familiar world of large bodies, orbits, and Newton's laws. The laws that describe atomic behaviour, the stationary states and transitions, reduce by correspondence, when applied to large systems, to Newton's laws.

The discovery of these laws by Heisenberg could itself have led to all we now know of quantum theory, but it was supplemented as a

* Professor Oppenheimer, this past year, presented for the British Broadcasting Corporation their annual distinguished series, The Reith Lectures. This article is adapted from the fourth in this series of six lectures which were presented by BBC's Home Service (see *The Listener*, December 10, 1954).

matter of history by new discoveries in related fields which make the task of understanding and exposition simpler and more direct. Yet even these are both unfamiliar and abstract; I fear that no exposition can be wholly without difficulty.

Our problem has to do with the so-called duality of wave and particle. On the one hand we have light, described in detail as a continuous electromagnetic wave with electric and magnetic fields, changing with a frequency that determines the light's colour, and with an amplitude that determines its intensity. The waves of light differ from radio waves only in one respect: their wave length is much shorter. They differ obviously from the waves we see on water, which are the more or less regular displacement of matter. But when we talk here of waves, in this account of wave-particle duality, as we shall have to, it will mean something quite abstract, something common to light and radio and water waves.

It will mean a state of affairs distributed in space and propagating with time, sometimes a harmonic like a pure note of sound and sometimes irregular like noise. It will mean that these disturbances in general add, so that two crests reinforce, and a crest and a trough tend to cancel. It will mean that the sum of two effects may not be greater than either, but smaller, as the phases of crest and trough indicate. It will mean that, if we leave more than one alternative for a particle or for light to go from one place to another, the chance of arriving may be greater than the sum of the chances or smaller than the sum of the chances, because of this interference of the waves that represent the alternatives.

When we deal with light, we deal with such waves; but we also deal, as Einstein discovered, with something sharp, discrete, and discontinuous—the light quantum. Whenever light acts on matter, or is produced by it, we find packets of defined energy and impulse, related to their frequency and their wave number by the universal proportionality of the quantum of action. How were these quanta to be thought of? Were they guided by the waves? Were they the waves? Were the waves an illusion, after all?

This turned out to be a universal quandary. De Broglie suggested and later Davison found that there were waves associated with electrons. Specifically Davison's experiment showed that electrons, too, when they are scattered by the regular disturbance of a natural crystal, exhibit the same signs of interference, the same unmistakable signature of the

super-position of waves as light and as X-rays; and later experiments showed that this is true of all the other particles as well—protons, neutrons, and the atoms themselves. It would be true of large objects also were it not that their wave length is small, because of smallness of Planck's constant, and becomes completely insignificant compared with their dimensions and with any practical possibility of determining their location and outline.

All the questions which puzzled men about the relations of Einstein's quanta and Maxwell's waves were thus to be equally sharp and equally troublesome for the wave and particle properties of matter. The resolution of these questions is the heart of atomic theory. They were brought to the point of crisis by another great discovery—Schroedinger's discovery of his wave equation.

In its original, bold form this was the discovery of a simple law for the propagation of electron waves—a natural generalisation of the connection between wave number and impulse, between energy and frequency, a generalisation nevertheless adequate to describe the gross features of atomic systems and most of the familiar properties of matter. This equation had many sorts of solutions. Some were stationary, unchanging in time, with a frequency and energy that corresponded to the stationary states of atoms. This same equation had other solutions of a very different kind, representing the trajectory of an electron as it might be seen crossing the Wilson cloud chamber. It had still other solutions, compounded by addition of several stationary states with their several proper frequencies. These were not stationary but varied in time with frequencies corresponding to the spectrum of atoms and molecules.

But what were these waves? What did they describe? How were they related to the ways in which we observe and study atomic systems, to Rutherford's probings, to the collisions and disturbances of atoms? Schroedinger understood that in some sense the world of classical physics would emerge from his equation, whenever the wave lengths were small enough; then the trajectories for bodies and planets would be like the geometric paths of light, the rays of optics. But what would the waves mean when this was not the case?

It would have been no answer to this question to attempt to interpret the waves as an essentially mechanical disturbance in some underlying mechanical medium; for the questions which needed answering had to do with the problems of stationary states, and the behaviour of elec-

trons, and not with a sub-stratum inaccessible to observation. Nor was such a path followed. The discouraging outcome of an analogous attempt with electromagnetic waves was conclusive. It did not seem reasonable, nor in fact has it ever proved possible, at a time when the very foundations of classical mechanics were being altered, to reinterpret this revolution in classical mechanical terms.

There was another false start. It was at one time suggested that the waves, as they spread and moved, in some sense represented the changing shape, extension, and flow of the electron itself; when the disturbance grew larger the electron grew larger; when the wave moved faster the electron moved faster. But to this interpretation there was an insuperable obstacle. Whenever we looked for the position of the particle, looked not directly with the eye, but with the natural extension of looking with a microscope, we did not find it spread out; we never found part of it in the place where we were looking. Either it was there or it was not there—the whole or none of it. Whenever we tried to measure the velocity of an electron or its impulse, we never found that part of it was moving with one speed and part with another; there was always one electron, one philosophy, one answer to an experimental inquiry. The spreading of the waves in space thus did not meant that the electron itself spread; it meant that the probability or likelihood of our finding the electron, when we look for it, spread as the wave does.

And thus it was that these waves were recognised as describing a state of affairs, as summarising information we had about the electron, as very much more abstract waves indeed than we had hitherto encountered in physics. Their interpretation was statistical as well as abstract: where a disturbance was large, there we were likely to find the electron if we looked for it; where it was small, unlikely. If the disturbance had ripples in which a certain wave length was prominent, a measurement of the momentum would be likely to give us a value corresponding to that wave length. This clearly is qualitative talk. Quantitative rules for assigning a wave function to describe the outcome of an observation—or of other certain forms of knowledge, such as that of an atom in its state of lowest energy—needed to be, could be, and were developed; and they are a part of quantum theory. Their exposition presupposes some mathematical talk and calls at least for a blackboard. Similarly, the simple rules which relate the magnitude or properties of a wave function to the expectations that it implies for one or another observation

are a rigorous and necessary part of the theory. But with these bonds to tie the wave to our knowledge and to interpret it for our prediction, the basis of the new physics has been laid.

It is a statistical physics, as indeed might have been expected from the statistical features of atomic transitions. Its predictions are in the form of assertions of probability and only rarely and specially in the form of certitudes. With this in mind, let us look again at our problem of interference, and of the two holes.

Let us think of an opaque screen with two holes in it. Let us think of light, if we will; or, better still, let us think of electrons of a given velocity and therefore a given wave length and direction. We can do two experiments with a source of electrons. In one, each hole in turn will be open for a little, while the other is closed; in the other, both holes will be open together. If we register the electrons on the far side of the screen, for instance, with a photographic plate, we see that the two patterns are radically different. In the one case, we have a transmission through each of the holes separately, with the characteristic diffraction pattern for that wave length and for holes of that diameter. These patterns are just added to one another on the photographic film. But if both holes are open at the same time, something else happens. The waves that come through one interfere with those that come through the other; spots that were blackened before are now untouched and new spots appear where the electrons do arrive.

If we try to think of this in terms of following the electrons through one or the other of the holes, we cannot understand how it can make any difference whether that hole through which the electron did not pass is open or shut; yet it does. If we argue that the effect can be traced to the interaction of electrons passing through the two holes, we can disprove this by noting that the pattern is not affected by reducing the number of electrons to the point where there almost never are two passing through the two holes at the same time. What we are observing is something characteristic of the behaviour of single particles, not of the interaction of several.

We are thus led to say that in this experiment a knowledge of which hole the electron passed through is in principle inaccessible to us, that it is just the possibility of its passing through one or the other that leads to the characteristic new interference phenomena, the new light spots and the new dark spots on the photographic film. We conclude that, if we should make provision for registering through which

hole the electron went, such as looking for it or observing the small push that it gives to the screen as it passes through, we would destroy the interference effects. We would then have the same result as if we had in fact opened and shut the holes successively.

We see the connection between these conclusions and the description of the state of affairs by a wave field in qualitative terms, rather closely paralleling the arguments that were made quantitative in the uncertainty principle of Heisenberg.

For we note that, if we were sure that the electron passed through one of the holes, the wave field would have to be restricted to that region; and that, if this were true, it would have to be composed not of a single wave length, or approximately a single one, but of waves of enough different wave lengths so that they can reinforce each other at one hole and vanish at the other; and we know that such waves have lost the coherent quality necessary for interference. A little more generally, the waves of a single wave length will correspond to an electron of a definite velocity or impulse, but in an ill-defined or undefined position; the waves that are localised to represent a definition of position will be broadly scattered in wave length and represent an undefined velocity or impulse. This complementary restriction on the degree to which a wave field can represent both a well-defined position and a well-defined impulse is universal; it is measured by the quantum of action. It holds not only for electrons but for the more complicated waves that describe complex systems, for atoms and nuclei and more composite bits of matter and more elementary ones. And the very fact that no wave field can give that complete definition of the position and velocity of an object which was taken for granted in classical physics is also a description of the limitation on the observations which in the real world we shall manage to make. It represents the fact that, when we study a system, making an experiment or an observation on it, we may—and in general we will, if we have prior knowledge before the experiment—be losing in whole or in part that prior knowledge. The experiment itself—that is, the physical interactions between the system and the equipment that we are using to study it—will not only alter what we previously knew, but will in general alter it in a way which cannot be followed without invalidating the measurement or observation we have undertaken.

To cite but one example: if in the problem of the two holes we try to detect which hole the electron has passed through by noticing the

push that it gives to the screen at that point, we shall have to leave a part of the screen free to respond to the push; and by this we lose all certitude as to where that part of the screen was when that electron passed through it. Many complex and detailed studies have been made of how this limitation of knowledge occurs in an experiment; but since the principle of complementarity, and the general adequacy of a wave field to describe a state of affairs, underlies the description of both the object and the instrument of observation, these examples only illustrate and make vivid what must generally be true: the universal limitation, in contrast to classical physics, of the extent to which all aspects of a physical system can be defined for the same system in the same instance.

In observing atomic systems, in observing a system where the finiteness of the quantum of action plays an important part, we have a wide range of choice in the kind of probe, the kind of experiment, the kind of experimental equipment we wish to make. To any of these, if it is a good experiment, there will be a meaningful answer which tells us what the state of affairs is. From this, and from the wave field which represents it, we can then make statistical predictions of what will happen in a subsequent experiment. The potentialities of measurement are varied. We can do one thing or another; there are no inherent limits on the choice of actions on the part of the observer. This is a very different view of reality from Newton's giant machine. It is not causal; there is no complete causal determination of the future on the basis of available knowledge of the present. The application of the laws of quantum theory restricts, but does not in general define, the outcome of an experiment. This means that every observation on a system reveals some new knowledge as to what its state is that did not exist before, and could not by analysis and mathematical computation have been obtained. It means that every intervention to make a measurement, to study what is going on in the atomic world, creates, despite all the universal order of this world, a new, a unique, not fully predictable, situation.

Even in a brief account other points need to be mentioned. We have almost lost the concept of equations of motion, having discovered that the very terms in which they are formulated—position, velocity, acceleration, and force—are not simultaneously applicable and do not, taken together, correspond to things that we know about the electron with enough accuracy to be meaningful for an atomic system. Instead what we can have is a knowledge of the state, summarising for us

what we have found by observation; and the analogue of the equation of motion must tell us how, in response to forces acting within the system or upon it, this state will change with time. This, it turns out, is just what Schroedinger's equation does. And once again this equation, when applied to the familiar contexts of massive bodies and great distances, where the quantum of action is in fact negligibly small, will describe for us waves so reasonably concentrated in space, so little dispersed about their average wave length, that the Newtonian orbit reappears in its unaltered, classical path.

But this condition—this emergence of an orbit—is a long way from the wave that describes the normal state of an atom. State and orbit, like position and impulse, are complementary notions; where one applies, the other cannot be defined, and for a full description we must be able to use now one, now the other, depending on the observation and the questions that we put.

When we speak here of observer and object, of instrument or probe, and system to be probed, we are not talking of the mind of man. We are talking of a division between the object of study and the means used to study it. That division can be made in more than one way. We may regard the α-particles that Rutherford used as an instrument, and their response as a measure of the state of affairs. We may regard the α-particle as a part of the system we are studying, and the slits that define its path or the fields that deflect it and the screens that detect it as the instrument. But whichever we do, the observation will always be transformed into some large-scale happening—some flash of light, some triggering of a circuit, some pointing of a pointer on the dial of an instrument—which is well defined and familiar and unambiguous, and where the question of our freedom to do one or another observation on it no longer is relevant. The atomic world has not lost its objective quality; but it attains this by means of those interlockings with experiment which we use to define one or another of its properties and to measure them.

It needs to be clear that what is described here is not an expression of mood or preference or taste; it is an exact, beautiful, quantitative, immensely versatile, and immensely successful science. It is what students learn when they prepare themselves for further researches in physics, or what engineers learn whose engineering involves a knowledge of the solid state of physical materials, or what chemists learn if they wish to understand the subtler features of chemical bonding or chemical

kinetics, or astronomers if they wish to know what things are like in the interior of the stars. One could go much farther in describing this discipline, even without mathematics; but the words would before long become cumbersome and unfamiliar and almost a misinterpretation of what in mathematical terms can be said with beauty and simplicity.

Even some of the more paradoxical features of quantum theory turn out to be related to practical matters of real importance. One of the earliest to be noted and the oddest is this: if, in familiar life, we roll a ball up a hill and it does not have enough vigour to get over the top, it will roll back on the same side; it will not get through the hill. But if we bombard such a hill with α-particles or electrons they may have a small chance of getting through, even when they cannot get over. This has a close analogy with the fact that very small objects do not cast sharp shadows in a beam of light. Light because of its wave nature bends around them. It corresponds to the fact that when we let electrons or other particles of definite energy encounter a barrier, neither the kinetic nor the potential energy alone can be completely well defined; and indeed, were we to try to detect the electron just as it passes through the hill, we should need an experiment that could give the electron enough energy to be quite legitimately on top of the hill. This penetration of barriers is not without importance. It accounts for the fact that the α-particles that Rutherford used could sometimes, after millions of years, escape from the nuclei through a high hill where electrostatic repulsion had imprisoned them. It accounts for the fact that in the sun and other stars nuclei having only very moderate energy occasionally come into contact and react. Thus the stars light the heavens, and the sun warms and nourishes the earth.

Another consequence of the wave-like character of all matter is that, when particles with very low velocity and very long wave length bombard other particles of matter, they may interact far more often than if these interactions were limited to their coming in contact. The very lack of definition of their relative position makes interaction possible, in some cases over distances characterised not by their dimensions but by their wave length. This is the circumstance which, among many others, enables the rare Uranium-235, as it occurs in natural uranium, to catch up enough of the neutrons which fly about to sustain a chain reaction in an atomic reactor.

There are even some odd things about the identity and the identifiability of the electrons themselves. That they are all similar we know.

Their inherent properties, their charge, their mass when at rest, are the same. We wish that we understood this better; some day, no doubt we shall; but we know that it is true. But if classical physics were the whole story, we could still, if we wished, always identify an electron and know that it was the same as the one we had seen before. We could follow it, not, it is true, without trouble, but without paradox without inconsistency, from where we first found it through its collisions and interactions and deflections and changes by keeping in touch with its trajectory. If it hit another electron, we would know which it was that came out in one direction and which in another. In fact this is not really true, except in those special instances where the collision is of such low energy that the two electrons can be described by waves which never overlap at the same place at the same time. As soon as that is no longer the case, we lose in principle all ability to tell one electron from another; and in atomic physics, where the electrons of an atom, and even the electrons of neighbouring atoms are not well defined in position and can often occupy the same volume we have no way of identifying the individual particle. This, too, has consequences. When two electrons collide, the wave that represents one of them and the wave that represents the other may, and do, interfere; and this gives rise to novel effects and new forms for the interactions produced by their electric repulsion. It is responsible for the permanent magnetism of magnets. It is responsible for the bonding of organic chemistry and for the very existence in any form that we can readily imagine of living matter and of life itself.

These examples are not given to perplex and bemuse. They are rather illustrations of how even the most paradoxical and unexpected consequences of the new mechanics, of wave-particle duality, and of complementarity are involved in an understanding of important and familiar features of the natural world, and of how massive is the system of understanding and knowledge of which they are a part